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An overview of a polyhouse dryer

A. Sangamithra [a,*], Gabriela John Swamy [a], R. Sorna Prema [a], R. Priyavarshini [a], V. Chandrasekar [b], S. Sasikala [c]

[a] Department of Food Technology, Kongu Engineering College, Tamil Nadu, India
[b] Agricultural Engineering College and Research Institute, Tamil Nadu Agricultural University, Tamil Nadu, India
[c] Department of Food Process Engineering, SRM University, Tamil Nadu, India

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ABSTRACT

Escalating demand for a cost efficient energy source has opened up opportunities for the utilization of solar energy. The abundance of solar energy is making a noticeable impact in the lives of rural people. This energy is being tapped for the drying of agricultural products. Numerous designs of solar dryers have been developed for safe and efficient drying. Polyhouse dryer (PHD) is one of them, which has been gaining importance in recent times for its cost efficiency and improved product quality. This paper reviews the significance of polyhouse dryer, in terms of its design and efficiency. The different existing models, materials of construction and products dried in polyhouse dryers have also been discussed.

Contents

* Corresponding author. Mobile: +91 8680909333.
E-mail address: asokmithra@gmail.com (A. Sangamithra).

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1. Introduction

Drying is a classical method of food preservation, which involves the removal of moisture through the application of heat to the product. The applied heat raises the vapor pressure of moisture in the product above the ambient air temperature and removes the moisture in the product. Therefore, drying extends the shelf life of product and provides a light-weight product for transportation and reduces storage space [1]. One of the traditional methods of drying is open sun drying. This process has several disadvantages such as spoilage of the product due to adverse climatic conditions, loss of material due to birds and animals, deterioration of the material by decomposition, insect infestation and fungal growth [2]. Also, the process is time consuming, labor intensive and requires large space. With cultural and industrial development, mechanical drying, the extremely energy intensive and expensive process, came into practice. Down the line, the introduction of solar dryers is considered to be the best alternative as a solution of all the drawbacks of natural drying and mechanical drying [3]. The energy efficient solar drying method can be utilized for the entire drying process or for supplementing other mechanical drying systems, thus reducing the total amount of fuel required and also producing better quality products. Solar dryers can reduce crop losses and improve product quality significantly when compared to the traditional methods of drying such as sun/shade drying [4]. The prominent feature of this dryer is the abundance of solar energy; hence the method is viable for reduction of moisture of agricultural produce at a commercial scale. The usage of solar dryers can be increased by overcoming the barriers such as cost of the solar drying systems, the lack of good technical information and good local practical experience [3]. Significant developments of the past decade in the solar drying of agricultural produce confirm that solar energy is considered more applicable to low-temperature in-storage drying systems and it has gained more importance in the last decade for drying grain and hay [2,5].

Solar dryers may be broadly classified into different types as given in Fig. 1 [6–8]. Basically, four types of solar dryers have been successfully employed for the drying of horticultural produce. They are (1) direct solar dryers, (2) indirect solar dryers, (3) mixed mode solar dryers and (4) hybrid solar dryers. In direct solar dryers, solar radiation is transmitted through the transparent cover and absorbed on blackened interior surface. Due to accumulation of energy, heat builds up within the dryer from the direct sun and also due to the green house effect [9]. This type of solar dryer is suitable for drying 10–15 kg of fruits and vegetables on domestic scale [10]. The polyhouse dryer belongs to the green house type of dryers. In indirect solar dryers, a separate solar collector is used to heat the air entering into the cabinet. The hot airflows as a result of the buoyancy forces resulting from the temperature differences up through the drying bed thereby producing the drying air [11]. This dryer is used for food materials sensitive to direct solar radiation. The performance of the dryer depends on the variations in insulation, ambient temperature, and relative humidity [12]. The heat required for the drying operation in mixed mode solar dryer is produced by the combined action of solar radiation incident on the produce and the preheated air in the solar collector [13]. The solar energy passing through the transparent sheet in the collector heats the absorber that transmits the heat to air [14]. The product on the bed absorbs the solar radiation leading to evaporation of moisture from the product. The increase in air temperature on the top of the product bed increases buoyancy-induced airflow rate [15]. Therefore, drying rate increases due to increased product temperature and buoyancy-induced airflow rate [16]. Hybrid solar dryers partly depend on solar energy. They utilize solar energy, electrical energy or fossil fuel based heating systems [17]. Motorized fans and pumps are used for air circulation. In hybrid solar dryers, photovoltaic module generated DC electrical power to drive a DC fan for maintaining the desired temperature inside the chamber used [18]. Major applications of hybrid solar dryers are in large scale commercial drying operations [19].

The justification for solar driers is that they are more effective than sun drying, with lower operating costs than mechanized driers [20]. Numerous designs have been proven technically; however none yet is widespread in use. An extensive study has been conducted on different types of direct solar dryers such as box/cabinet-type, tent-type, and polyhouse solar dryers for drying of agricultural produce [21–24]. Polyhouse dryers are now being increasingly used since they are a better and more energy efficient option [25]. A comprehensive review of polyhouse drying systems is presented in this paper.

2. Polyhouse dryer (PHD)

A polyhouse dryer is a unique and cost efficient method of drying agricultural products on commercial scale. It consists of a drying chamber, an exhaust fan and a chimney. The roof and the wall of a PHD are made by transparent plastic films that are mounted on a metal frame. The sheet has a transmittivity of approximately 92% for visible radiation which traps the solar energy during the day and maintains optimum temperature for drying of produce [26]. UV-stabilized films play an important role in polyhouse dryers. UV-radiation in the sun rays tends to cause changes in the organoleptic properties such as texture, color and flavor of food materials. Hence UV-stabilized polyethylene sheets are used to prevent such deterioration. The sheet allows only short wavelength which is converted into long wavelength when it strikes on the surface of product or a black body. Since the long wavelength cannot move out, it increases the temperature inside the dryer. Apart from the above mentioned advantages, the sheet has superior properties in terms of transparency, transmittivity, anti-corrosion property, self-adhesive, retraction ratio, tensile properties, tear-resistant, anti-puncture, water-proof, moisture-proof and dust-proof. Polycarbonate covers have been used recently for PHD construction [27]. A black surface inside the PHD improves the effectiveness of converting light into heat. Plastic sheets and glass covers have the distinct property to allow light to enter the dryer and retaining it inside the chamber. The trapped light is converted into heat energy to remove moisture from the produce. The dryer can be connected in series and hence its capacity can be enhanced as per requirement and it can be dismantled so that its transportation is easy from one place to another.

The objective of a polyhouse dryer is to maximize the utilization of solar radiation. Based on the mode of heat transfer, it is classified into passive and active polyhouse dryer. The passive mode dryer works on the principle of thermosyphic effect i.e. the moist air gets ventilated through the outlet provided at the roof or through the chimney of the dryer. For active polyhouse dryer, there are two energy sources namely the air saturation deficit and the incident global solar radiation [28]. Both natural and forced convection methods circulate the hot air to the food material. One of the differences is that, at the initial stage of drying, the value of mass transfer coefficient is double in the active mode than in passive polyhouse dryers.

Nomenclature

M_w	quantity of water removed, kg
M_d	dry matter of product, kg
M_i	initial moisture content of product, % d.b.
M_f	final moisture content of product, % d.b.
Q	total energy required for drying, kJ
C_d	specific heat of product, kJ/kg °C
T_2	temperature inside the polyhouse dryer, °C
T_1	ambient air temperature, °C
C_p	specific heat of water, kJ/kg °C
λ	latent heat of vaporization of water, kJ/kg
t	total drying time, h
A_c	collector area of solar tunnel dryer required, m^2
Q_t	energy required per hour for drying of product, kJ/h
I	total solar radiation incident on the dryer, kJ/hm^2
η	overall thermal efficiency of solar dryer, %
a	area of hemi-cylindrical shape of PHD, m^2
r	radius of dryer, m
L	length of dryer, m
D	diameter of dryer, m

2.1. *Design considerations for PHD*

2.1.1. *Collector area required for drying*

Collector area of solar tunnel dryer required for drying was calculated using the following equation:

$$A_c = \frac{Q_t}{I\eta 0.68} \tag{1}$$

2.1.2. *Area of PHD*

Area of hemi-cylindrical shape of PHD was calculated as follows:

$$a = \pi r(r+L) \tag{2}$$

2.1.3. *Diameter of PHD*

Diameter of PHD varies between 3.5 and 4 m and is kept as constant for easy entry and other convenience [29]. Radius of the solar dryer was calculated as follows:

$$r = \frac{d}{2} \tag{3}$$

2.1.4. *Length of PHD*

Length of polyhouse dryer was calculated as follows:

$$L = \frac{(a-\pi r^2)}{\pi r} \tag{4}$$

2.1.5. *Floor area of PHD*

Floor area of polyhouse dryer was calculated as follows:

$$A = Ld \tag{5}$$

2.1.6. *Quantity of moisture removed from the product*

Henderson and Perry [30] suggested a model to determine the quantity of water removed to dry the product from initial moisture content to safe storage moisture content.

$$M_w = \frac{M_i - M_f}{100} M_d \tag{6}$$

2.1.7. *Total energy required for drying*

Total energy required for drying was calculated using the following equation:

$$Q = M_d C_d (T_2 - T_1) + M_i C_p (T_2 - T_1) + M_w \lambda \tag{7}$$

2.1.8. *Drying rate*

Drying rate was calculated as follows:

$$k = \frac{M_w}{t} \tag{8}$$

3. Discussion

3.1. *Construction of PHD*

Shahi et al. [26] fabricated a solar polyhouse tunnel dryer (Fig. 2) having length of 5 m, breath of 4 m, central height of 3.2 m and side heights of 2.5 m left and 1.5 m right for fruits and vegetables. The PHD consisted of a drying chamber, a small exhaust fan and a metal duct. The dryer was covered with a transparent UV stabilized polyethylene plastic foil of 0.2 mm thickness. The top surface of the dryer was curved in shape in order to increase the area of radiation with an inclination of 30°. The dryer was positioned in the north–south direction so that, radiation from the sun would not be disturbed. A fan of 1000–1200 m^3/h airflow rate capacity and 1 kW power was also installed. The concrete floor was painted black for better absorption of solar radiation. A glass wool insulation of 2 in. thickness was provided, to reduce heat loss through the floor. The capacity of the tunnel ranged from 1 to 1.5 quintal of fresh fruits and vegetables depending upon the material and thickness of the spreading layer.

Sevada [29] designed and developed a walk-in type hemi-cylindrical solar tunnel dryer (Fig. 3) for drying of dibasic calcium phosphate. The hemi-cylindrical metallic frame structure was covered with UV-stabilized semitransparent polyethylene sheet of 200 μm thickness and had a base area of 3.75×21.00 m^2 as in Fig. 4. The orientation of solar tunnel dryer is in the east–west direction. A slope of 2–3° was given along the length of the tunnel. An exhaust fan of 0.75 kW power, having volume flow rate of 1500 m^3/h was also provided at the upper end of the tunnel for occasional removal of moist air to maintain humidity at a preset level inside the tunnel. The average relative humidity of the inside air was between 30% and 40%. The design of an improved solar tunnel dryer has been tested by Janjai and Keawprasert [31]. The dryer consists of the solar collector and the drying unit. The PE plastic sheets were replaced by polycarbonate plates fixed with the side walls of the dryer. The polycarbonates plates had an inclination angle of 5° for the drainage of rain. A rectangular window was made at the side wall of the drying unit for loading and unloading products. A high density foam insulator was sandwiched between two galvanized metal sheets. A 15 W solar cell module was used to power a dc fan for ventilating the dryer. The area of the solar collector and the drying unit was 1.2×4 m^2 and 1.2×5 m^2, respectively.

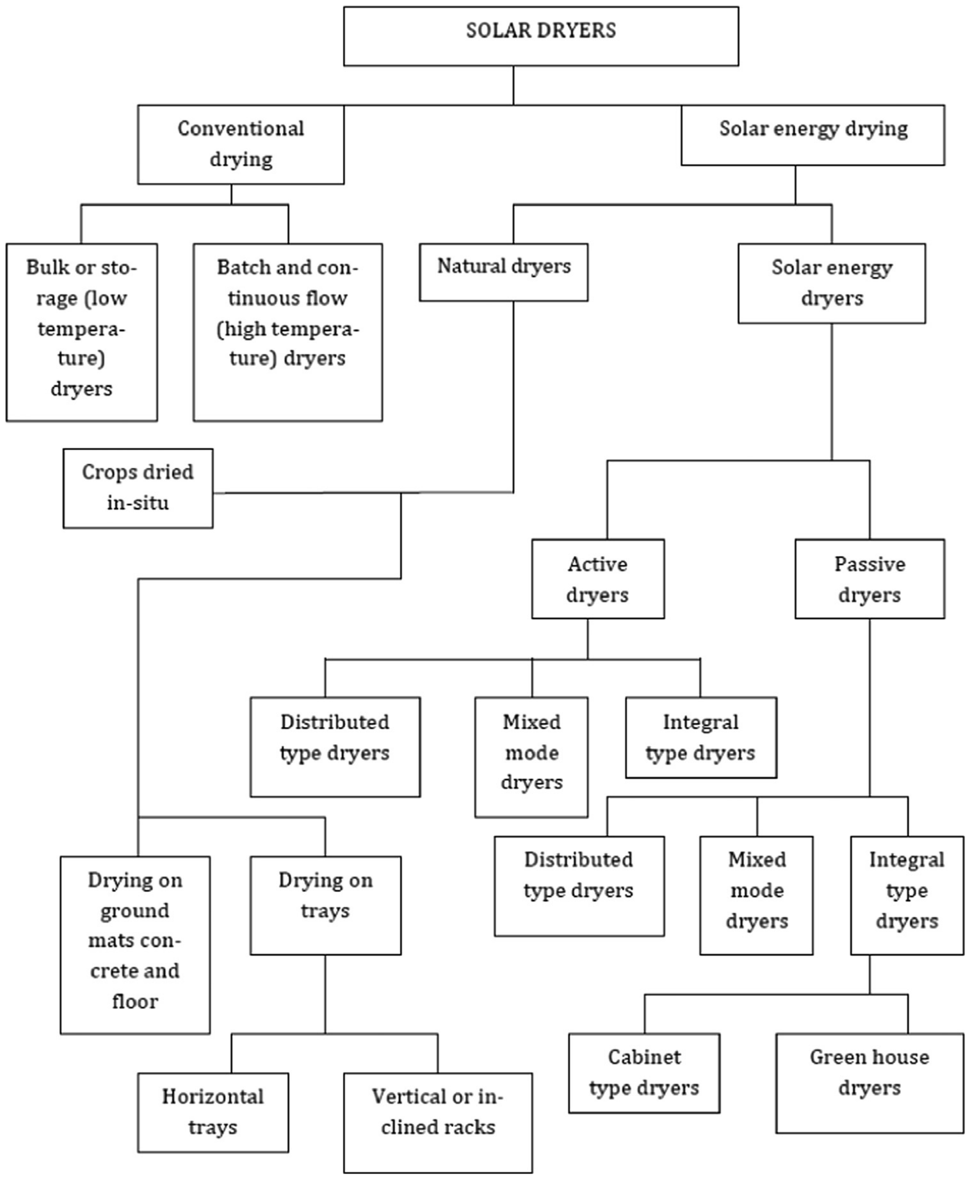

Fig. 1. Classification of solar dryers [6].

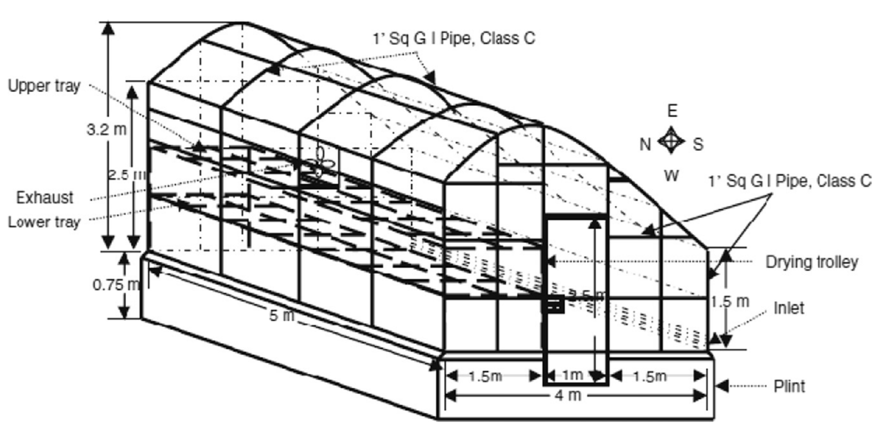

Fig. 2. Schematic diagram of PHD [35].

A large scale parabolic shape active green house dryer having 1000 kg capacity covered by 6 mm thick polycarbonate sheet with nine DC exhaust fans powered by 50 W solar cell modules was developed by Janjai et al. [27]. The dimension of the dryer is 7.5 m wide, 20.0 m long and 3.5 m high. The dryer was designed into a parabolic shape in order to reduce a wind load, in the case of

a tropical storm. The front side wall of the dryer has two air inlets. The maximum capacity of these dryer for fresh fruit such as banana, was approximately 1000 kg. The dryer was in the north–south orientation. A pictorial view of the dryer and the diagram of the structure of the dryer are shown in Figs. 1 and 2, respectively. Ekechukwu and Norton [32–34] designed a simple natural circulation solar dryer covered with a polythene cover. It consisted of a semicylindrical drying chamber with a cylindrical chimney at one end, while the other end was equipped with a door for air inlet and access to the drying chamber. The drying chamber measured approximately 6.67 m long by 3.0 m wide by 2.3 m high. The chimney had a maximum possible height of 3.0 m above the chamber and a diameter of 1.64 m.

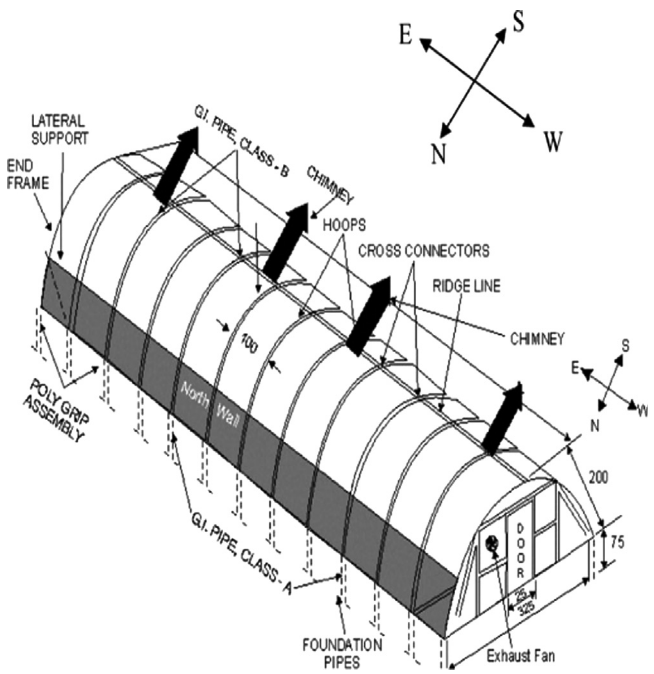

Fig. 3. Schematic diagram of hemi-cylindrical solar tunnel dryer [30,37].

Fig. 4. Pictorial view of hemi-cylindrical solar tunnel dryer [30].

Kulanthaisami et al. [35] used a semicylindrical solar tunnel dryer covered with UV stabilized semitransparent polythene of 200 μm, for drying coconuts. The solar air collector cum drying chamber of solar tunnel dryer consists of 18 m length and 3.75 m width for drying 5000 coconuts per batch. The plastic sheet was opaque to long wave radiations; these radiations were trapped inside the dryer and raised the tunnel temperature. A single layer polythene film for the cover of solar tunnel dryer was preferred due to material economy and easy handling. The tunnel had a tilt of 10–15° horizontally to generate natural convection flow in the dryer. An exhaust fan of 1700–1900 m^3/h airflow rate capacity of 0.9 kW rating for removing moist air was also provided near door of the dryer.

3.2. Performance evaluation of PHD

Drying behavior in PHD depends on size, shape and thickness of the product, initial and final moisture content and weather condition. Several studies on crops like cauliflower, apple, pear, tomato, cabbage and leafy vegetables showed that the reduction of moisture content soon after harvesting in a polyhouse solar dryer improves the storage life of the produce [36]. Researchers have performed a comparison study between polyhouse type solar drier and open sun drying for different agriculture products such chilli [37,38], copra [37], onion, okra, tomato, mango and pineapple [39]. The comparison of drying behavior of various agricultural crops in open sun drying and PHD is tabulated in Table 1.

Shahi et al. [26] investigated the thermal performance of PHD under different testing conditions. The temperature inside the dryer was 62–76% higher than the ambient temperature. The relative humidity (RH) inside the PHD varied between 21% and 74% as compared to outside RH which ranged from 40% to 75%. It was found that PHD was helpful in reducing the time taken for dehydration by about 40–55%. He also concluded that the high temperature coupled with proper air circulation produced a higher drying rate in PHD as compared to open sun drying leading to reduction in dehydration time.

Sevada [20] studied the performance of UV stabilized polyethene covered solar tunnel dryer for drying of aonla pulp. It was observed that the maximum airflow rate inside the tunnel was 7374.6 m^3/h at 13 h, while minimum airflow rate was 5355 m^3/h at 9 h. Average air temperature attained inside the solar tunnel dryer was about 21 °C higher than the ambient temperature. The relative humidity inside the dryer varied from 26% to 50% during full load condition. Sethi and Arora [40] improved the east–west

Table 1
Performance of polyhouse solar dryer and open sun drying for agricultural produce.

S. no.	Product	Temperature (°C)		Moisture content (% w.b.)		Drying time		Reference
		Ambient	PHD	Initial	Final	Sun drying	PHD	
1	Coconut	26–33.5	45–55	55	6.3	5 days	3 days	[35]
2	Chilli	36	56.7	83.4	9	7–10 days	2–3 days	[38]
3	Aonla	40.8	61.7	73.61	11.10	40 h	16 h	[20]
4	Capsicum	27.4–32.5	50–70	92.2	3.8–5.6	32 h	21 h	[26]
5	Tomato	27.4–32.5	50–70	93.8	8.2–10.4	38 h	21 h	
6	Cabbage	27.4–32.5	50–70	92.8	3.6–3.8	32 h	18 h	
7	Spinach	27.4–32.5	50–70	92.4	3.2–5.6	32 h	14 h	
8	Carrot	27.4–32.5	50–70	86.8	4.4–8.2	32 h	21 h	
9	Apple	27.4–32.5	50–70	84.2	4.6–8.6	52 h	25 h	

orientation of conventional green house solar dryer using inclined north wall reflection. An enhanced drying rate was observed by using north wall reflection principle which facilitated the product to completely receive the reflected beam radiation in addition to the direct total solar radiation through the horizontal surface.

Sacilik et al. [41] compared the drying performance of tomato in solar green house dryer and open sun drying. It was found that the proposed dryer took four days to dry the tomato whereas open sun drying took five days to dry. The quality and color of the dried tomato in the dryer was far superior to naturally dried tomato. Joy et al. [42] used a German-made solar dryer to dry red chilies and reported that two days were taken for optimum drying of red chilies in solar tunnel dryer, whereas, it took 7–10 days by the conventional method. They also found favorable results regarding better qualities like cleanliness and texture of dried products. An experiment was conducted to dry banana, chilli and coffee. The drying time was only five days for banana in the proposed solar green house dryer, whereas open sun drying took seven days. The drying time for chilli was just 3 days in this dryer while it took 5 days in open sun drying. However, coffee took 2 days to dry in the proposed dryer while the natural dryer needed four days. The quality and color of green house dried products were far better than that in natural sun drying [27].

Mangaraj [43] inferred from his experimental results, that open sun drying took 150 and 102 h whereas green house solar dryer took 90 and 66 h to reduce moisture content from 300 to 8% and 9% (d.b.) for unpunched and punched chili, respectively. Singh et al. [44] observed that the minimum and maximum temperature inside the polyhouse dryer was 20 °C and 44 °C during winter season. The leafy vegetables were dehydrated within one day at the loading rate of 4–5 kg/m^2, whereas other vegetables were dried within 2 days at loading rate of 8–10 kg/m^2. Kaewkiew et al. studied the performance of a large-scale solar dryer for drying chilli and concluded that the solar dryer consumed less time as compared with the open sun drying, and the color of products dried in the solar dryer is better than natural sun dried samples [45].

3.3. Efficiency of a polyhouse dryer

According to Boonyasri et al. the drying efficiency of the dryer is defined as the ratio of energy output of the dryer to energy input in the dryer [46]. The efficiency of the polyhouse dryer was calculated using the following formula:

$$Dryer\ efficiency = \frac{M_w \lambda}{I_{av} A t} \times 100$$

Solar radiation input on the dryer is given by

$$I_{av} = A \int_0^t G\, dt$$

where M_w is the moisture evaporated (kg), λ is the latent heat (kJ/kg), I_{av} is the average solar input (kW/m^2), G is the solar radiation at time t (W/m), A is the dryer area (m^2) and t is the drying time (s) [47]. Anil et al. observed a maximum inside temperature in natural and forced convection as 40.6 and 41.4 °C respectively. It was found that by forced convection, the drying efficiency increased by 2%. The maximum relative humidity in natural and forced convection was found to be 62.6% and 42.8% respectively. It was concluded that the relative humidity for forced convection is less than that of the natural convection, hence the drying rate of the forced convection is efficient than natural convection by 31% [48]. Pickup efficiency is useful for estimating the actual quantity of moisture evaporated from the product inside the solar dryer. The pick-up efficiency is defined as the ratio of amount of moisture picked up by air inside the dryer to the theoretical capacity of air to absorb moisture [49,50]. It can be calculated using the following formula:

$$\eta = \frac{h_0 - h_i}{h_a - h_i}$$

where h_o is the absolute humidity of air leaving the drying chamber, h_i is the absolute humidity of air entering the drying chamber, and h_a is the adiabatic saturation humidity of the air entering the dryer. Pick-up efficiency generally decreases with decreasing moisture content in the product.

Rathore and Panwar designed a passive type walk in polyhouse solar dryer for drying surgical cotton was found to work efficiently for a batch of 600 kg. The system was found to save about 25.37USD/day. The authors further recommended that this technology can contribute long-term benefits in terms of saving fuel and environment, higher effectiveness and productivity [25]. The performance of polyhouse solar dryer was found better than open sun drying in terms of drying time and hygienic conditions and resulted in efficient drying at low relative humidity [26].

3.4. Mathematical models

The assumptions in developing a mathematical model [27] for polyhouse dryer are as follows:

(a) The airflow is unidirectional and there is no stratification of air inside the dryer.
(b) The products are dried in thin layers and calculation is based on the thin layer drying model.
(c) The specific heat of the air, the cover and the products are constant.

3.4.1. Energy balance equations

The balance of energy on the polycarbonate cover is the sum of rate of thermal energy transfer between the air inside the dryer and the cover due to convection, rate of thermal energy transfer between the sky and the cover due to radiation, rate of thermal energy transfer between the cover and ambient air due to convection, rate of thermal energy transfer between the product and the cover due to radiation and rate of solar radiation absorbed by the cover.

The energy balance of the air inside the dryer is the sum of the rate of thermal energy transfer between the product and the air due to convection, rate of thermal energy transfer between the floor and the air due to convection, rate of thermal energy gain of the air due to sensible heat transfer from the product to the air, rate of thermal energy gained in the air inside the dryer due to inflow and outflow of the air in the dryer, rate of overall heat loss from the air in the dryer to the ambient air and rate of solar energy absorbed by the air inside the dryer from solar radiation.

The energy balance of the product is the sum of the rate of thermal energy received from air by the product due to convection, rate of thermal energy transfer between the product and the cover due to radiation, rate of thermal energy lost from the product due to latent heat loss from the product and rate of thermal energy absorbed by the product.

The energy balances on the PHD floor is the sum of the rate of convection heat transfer between air in the dryer and the floor, rate of conduction heat transfer between the floor and the ground and rate of solar radiation absorption on the floor.

3.4.2. Mass balance equation

The accumulation rate of moisture in the air inside dryer is the sum of the rate of moisture inflow into the dryer due to entry of ambient air, rate of moisture removed from the product inside the

dryer minus the rate of moisture outflow from the dryer due to exit of air from the dryer.

3.4.3. Thin layer drying equations

The thin layer drying equations generally used for PHD are given in Table 2. The reduced χ-square, root mean square error (RMSE) and modeling efficiency (EF) were used as the primary criterion to select the best equation to account for variation in the drying curves of the dried samples. Reduced χ-square is the mean square of the deviations between the experimental and calculated values for the models and was used to determine the goodness of the fit. The lower the value of reduced χ-square, the better the goodness of fit. The RMSE gives the deviation between the predicted and experimental values and it is required to reach zero. The EF also gives the ability of the model and its highest value is 1.

Fudholi et al. evaluated the performance of solar drying in the Malaysian red chili. A non-linear regression method was used to fit the drying models. The Page model resulted in the highest R2 and the lowest mean bias and root-mean-square errors [8]. Panwar et al. investigated the thin layer drying characteristics of Fenugreek leaves in a PHD. The leaves were dried from a moisture content of 89% (w.b.) to 9% (w.b.) in 16 h. The drying data were fitted to eleven drying kinetics models and of these Verma et al. had the best fit. The energy efficiency during the study varied from 0.841% to 1.613% [51]. A study was conducted on thin layer solar drying of apricots [52]. The logarithmic drying model was found suitable for the single layer solar drying of apricots with a regression coefficient of 0.994. The statistical parameters χ^2, mean bias error (MBE) and root mean square error (RMSE) favored this model among others. Akpinar studied the thin-layer drying characteristics of mint leaves, and, performed energy analysis of solar drying process of mint leaves. The drying data were fitted to ten models. Among the models, the Wang and Singh model was found to be best to explain the thin-layer drying characteristics of mint leaves. The energy analysis throughout solar drying process was estimated using the first law of thermodynamics. Energy utilization ratio (EUR) values varied between 7.8% and 46.3%. Energy utilization ratio decreased with increasing drying time and ambient temperature [53].

El-Beltagy et al. conducted thin layer solar drying experiments on strawberry. The best fit for various shapes of strawberry was obtained by the Newton model with R^2 in the range of 0.97–0.98 and low values χ^2 ranging from 0.0102 to 0.0046. The researchers also indicate that the drying constant was greatly affected by product surface area, drying air temperature and ratio projected surface area to product mass [54]. The thin layer drying of tomatoes by Bagheri et al. showed that the Page model was found to be the best to predict the moisture content at varying thicknesses and air velocities [55]. According to Fadhel et al. the logarithmic model gave R^2 of 0.94392, $\chi^2=0.00316$ and RMSE= 0.05621 for the solar drying of peppers. The author suggested that the dryer can be improved to become more competitive to the solar air dryer, by increasing inside air temperature and then reducing the inside air humidity through the using of solar air heater [56].

3.4.4. Simulation models

Manoj and Manivannan used the partial differential equations (PDE) toolbox in MATLAB to model heat conduction of drying cocoa beans from the Crank–Nicholson method and obtained numerical approximation for the solution. It was found from simulation that the dryer performed at its optimal range and cocoa beans were dried to a moisture content of 7% within 7 days. It was suggested that the performance of dryer was enhanced by the heated air at very low humidity [57]. Jain and Tiwari also developed mathematical models to predict the crop temperature, temperature of drying chamber and moisture evaporation for open sun drying and also under active and passive mode green house dryer. The predicted models were validated with experimental observations for drying of cabbage and peas. The predicted values were in good agreement with experimental observations with high coefficient of correlation [58]. Janjai et al. developed a set of partial differential equations to describe heat and mass transfer during drying of chilli, coffee and banana using the finite difference method. The simulated results were in reasonable agreement well with the experimental data. The author also recommended that the developed model can be used for designing solar dryer at any other locations [27].

3.5. Socio-economic viability

The traditional methods of drying under direct sunshine is a slow process with problems like dust contamination, insect infection and spoilage due to unexpected climatic changes. This can be overwhelmed by the use of conventional fuel fired or electrically operated dryers. However, in rural areas, the supply of electricity is not available or it is too expensive for drying purpose. The fossil fuel fired dryers possesses financial barriers due to large initial and running cost that these are beyond the reach of small and marginal farmers. In such cases, the polyhouse solar dryer can be utilized in rural areas in developing countries as a better alternative to dehydrate the agricultural produce without any difficulties. Also the use of polyhouse type solar dryers can result in emission reduction if conventional fuels are replaced. The execution of improved technologies can have positive socio-economic impacts on food security and local income generation. It was found that the lifetime cost of drying with solar power is

Table 2
Mathematical models applied to drying curves.

Model	Equation	Reference
Newton	$MR=\exp(-kt)$	[4,41,52,61]
Page	$MR=\exp(-kt^n)$	
Modified page	$MR=\exp(-kt)^n$	
Henderson and Pabis	$MR=a\exp(-kt)$	
Modified Henderson and Pabis	$MR=a\exp(-kt)+b\exp(-gt)+c\exp(-ht)$	
Logarithmic	$MR=a\exp(-kt)+c$	
Two term	$MR=a\exp(-k_0t)+b\exp(-k_1t)$	
Two term exponential	$MR=a\exp(-kt)+(1-a)\exp(-kat)$	
Verma et al.	$MR=a\exp(-kt)+(1-a)\exp(-gt)$	
Approximation of diffusion	$MR=a\exp(-kt)+(1-a)\exp(-kbt)$	
Wang and Singh	$MR=1+at+bt^2$	
Midilli et al.	$MR=a\exp(-kt)+bt$	

only a third of the cost of using a dryer based on conventional fuels [59].

The material and manufacturing cost of polyhouse solar dryer of 1–1.5 quintal capacity was approximately Rs. 80,000. About 7373 kWh of electricity was estimated for an annual output, in the absence of PHD. The payback period was calculated and it was observed that the initial investment would be recovered within 1.5 year approximately [26]. Similarly a PHD designed by Janjai et al. resulted in reduced drying time and high quality dried products. The researchers estimated a payback period of 2.5 years for the PHD [27]. According to Janjai et al. the price of dried products obtained from PHD dryer was found to be 20% higher than that obtained from the open sun drying and the estimated payback period was 2.3 years [60]. A polyhouse dryer can function successfully and efficiently with minimum maintenance at low cost. With no further disadvantages, it could be a substitute to the conventional dryers thereby making it assessable and affordable by local farmers in the rural areas.

4. Conclusion

A comprehensive review of the various designs of polyhouse solar dyers for drying of food materials has been discussed. The design is based on the geographic location, production throughput and flexibility requirements. The effect of a poor design can have a long-term impact on the life of the dryer. Based on the previous literatures, it is concluded that

- during the initial stages of drying, the mass transfer coefficient under active mode polyhouse dryer is double than that of passive mode,
- the temperature inside the dryer was 62–76% higher than the ambient temperature,
- the relative humidity inside the dryer varied from 26% to 50% than the ambient relative humidity,
- the price of PHD dried products was found to be 20% higher than that obtained from the open sun drying,
- the PHD dryer took less drying time when compared to open sun drying,
- the quality and color of polyhouse dried products were far better than that in natural sun drying, and
- the estimated payback period of PHD was approximately 1.5–2.3 years.

From the work carried out to date on polyhouse drying of agricultural produce, it is inferred that the solar dryers can be used to a great extent. It is recommended that the farmers should use polyhouse solar dryers in their farms. Hence the polyhouse dryer is a boon to small scale farmers.

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